Polarization Compensation: a passive approach to reduce heterodyne interferometer nonlinearity

Oliver P. Lay and Serge Dubovitsky

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

Cyclic errors due to optical leakage limit the precision of displacement measurements made with optical interferometers. A method for real-time estimation of the leakage components is introduced, and is used to implement a novel 'passive' technique for suppression of cyclic nonlinearities, using only adjustments of existing polarizers and quarter-wave plates. This method is used to reduce the cyclic error from 3 nm to 300 pm, for an interferometer operating at a wavelength of 1320 nm.

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Optical interferometers are the instruments of choice for applications requiring sub-micron position knowledge. Examples range from semiconductor lithography to inter-spacecraft range measurement. Of the many possible optical configurations, the heterodyne interferometer is one of the most popular. While this paper will address the configuration shown in Figure 1, the techniques described apply to a wide range of designs based on polarizing optics.

A single laser source is split; the two arms are given different frequency-shifts, and polarized to give two beams with optical frequencies ν_1 and ν_2, and orthogonal linear polarizations. The collimated beams are combined at the Injection PBS. A small fraction of each is picked off at the Reference BS and mixed by the Reference polarizer. The Reference photodetector generates a heterodyne beat frequency at ν_A - ν_B. Most of the light propagates to the Main PBS; the p-polarized Beam B passes straight through, and the s-polarized Beam A makes a round-trip between the Target and Fiducial retro-reflectors, changing its polarization state as follows. The s-polarization reflected by the Main PBS is converted to right circular polarization (RCP) at the Target QWP, then becomes LCP after reflection at the Target. A second pass through the Target QWP converts it to p-polarization that passes through the Main PBS, becoming RCP, then LCP, then s-polarization that is reflected towards the Signal Polarizer at the Main PBS. The two beams are then mixed at the Signal Polarizer and a heterodyne beat at ν_A - ν_B is produced by the Signal photodetector, with a phase that changes by 2π for every half-wavelength shift of the Target retro-reflector with respect to the Fiducial. This phase information is extracted by measuring the phase difference between the two photodetector outputs.

In practice, various leakage terms mean that the phase difference is not a perfectly linear function of the target displacement, thus limiting the accuracy that can be achieved[1-3]. The most important term is shown in Fig. 1, where a small fraction (~0.1%) of s-polarized Beam A leaks through the Main PBS and follows the Local path. This results in an additional heterodyne beat at the output of the Signal photodetector, whose phase does not depend on the Target retro displacement, that gives the interferometer response vs displacement a cyclic error that repeats every half wavelength. The amplitude of this error is given by $\Delta x = (\lambda/4\pi)\,\varepsilon^{1/2}$, where ε is the fractional leakage power. For $\varepsilon = 0.001$ and $\lambda = 1300$ nm, $\Delta x \approx 3$ nm.

Several techniques have been proposed for reducing cyclic error in polarizing heterodyne interferometers, including dithering the target retro displacement, modulating the target beam frequency ν_1[4], phase modulation of the source laser light[5], and adding a second signal photodetector[6]. All of these involve a significant increase in the complexity of the signal processing or additional hardware. This paper describes a new method to reduce cyclic error, simply by optimizing the orientations of the polarizers and waveplates in the system.

Cyclic error is due to optical leakages resulting from mis-alignments and non-ideal components. The polarization extinction ratios on transmission and reflection for even a high quality polarizing beamsplitter cube are significant. Typical values are $X_T=T_s/T_p$~0.1% and $X_R=R_p/R_s$~5% [7], indicating, for example, that 5% of incident p-polarization will leak into the reflection path. As a result, the light arriving at the Signal Polarizer in Fig. 1, in addition to the two desired components, contains 7 leakage components specified in Table 1.

The first two terms, A_{Ts} and B_{Lp}, are the nominal signals, and the third term, A_{Ls}, is the inevitable straight-through leakage of the s-polarization of Beam A, due to the non-zero X_T of the Main PBS. These are the examples shown in Fig. 1. The corresponding electric field vectors arriving at the Signal Polarizer are illustrated in Fig. 2. It is impossible to selectively null the straight-through leakage A_{Ls} by rotating the Signal Polarizer, because the leakage is co-aligned with the desired A_{Ts} component. However, if the straight-through leakage of Beam A also had a p-polarization component (A_{Lp}), equal in magnitude to A_{Ls}, then the resultant electric field at frequency ν_A would be blocked by the Signal Polarizer, as shown in Fig. 2. In other words, deliberately introducing an additional leakage component, orthogonally polarized to the inevitable A_{Ls}, enables us to eliminate both with the Signal Polarizer!

This additional component, listed as the fourth term in Table 1, requires a component of p-polarization in Beam A incident on the Main PBS, where it will be transmitted without attenuation onto the Signal Polarizer. This p-polarization can be introduced in two ways: (1) rotation of the Injection PBS with respect to the Main PBS or (2) rotating the Target polarizer to generate a p-polarized component to Beam A before the Injection PBS; reflection at the Injection PBS attenuates this component by a factor of ~20. This second approach is the most convenient. If X_R=5%, then rotating the Target polarizer by ~8 degrees generates an A_{Lp} component with magnitude equal to the A_{Ls} component. In practice, nulling the straight-through leakage requires an adjustment of both the Target and Signal polarizers (see alignment procedure below). Computer simulations show that the primary reason for this is likely to be the differential phase response of polarizing beamsplitters to s- and p-polarization. For example, the p-polarization component of Beam A experiences a slightly different phase shift on reflection at the Injection

PBS than the s-polarization component of Beam A. Slight ellipticity in the response of the polarizers may also contribute.

Having dealt with the third and fourth terms in Table 1, we are faced with another five. The fifth and sixth components, A_{Tp} and B_{Ls}, are benign, however, because they share the same optical frequency and propagation paths as the desired components A_{Ts} and B_{Lp}. Differing only in polarization, they do not contribute to the cyclic error.

Two leakage mechanisms produce B_{Ts}. Any s-polarization present in Beam B before the Main PBS, due to misalignment of the Injection PBS and Main PBS, for example, will get reflected into the Target path and mixes with A_{Ts} to produce a heterodyne beat that is insensitive to displacement of the Target retro, resulting in a cyclic error. The magnitude of this leakage can be adjusted by rotating the Local polarizer to produce s-polarization at the input of the Injection PBS, only 0.1% (=X_T) of which, however, is transmitted towards the Main PBS. The second mechanism arises from the 5% (=X_R) of the p-polarized Beam B reflected into the target path by the Main PBS. Most of this is rejected from the target path as s-polarized light on the return trip through the Main PBS, but imperfections in the Target QWP (both intrinsic, and through misalignment) lead to a small fraction of p-polarization that passes through the Main PBS and ends up as B_{Ts} at the Signal Polarizer. The resultant total level of B_{Ts} can be minimized by using one leakage path to cancel out the other, i.e. adjust the Local polarizer and the Target QWP to obtain components with equal magnitude but opposite sign.

The eighth term, B_{Tp}, is very small, requiring a chain of at least three leakage mechanisms. For example, 5% (=X_R) of the p-polarized Beam B leaks into the target path at the Main PBS, which is converted to s-polarization of which only 0.1% (=X_T) passes through the Main PBS, which then becomes p-polarization of which only 5% (=X_R) is reflected out to the Signal Polarizer. Only 0.00025% of Beam B will complete this trip. Other permutations result in similarly small values.

The final term in Table 1, A_{2Ts}, is 'twice around' leakage. A fraction of Beam A (X_T=0.1%), propagating from the Fiducial retro back to the Main PBS, is transmitted instead of reflected, and makes a second return trip between the retro-reflectors. The phase of this term is now doubly sensitive to displacement of the Target retro, which results in a cyclic error with amplitude of ~3 nm (assuming $\lambda = 1300$ nm, $\varepsilon = 0.001$, and no optical loss in the target path). For every 6 dB increase in target path optical loss, the cyclic error is reduced by a factor of 2. Attenuation in the target path is the only option for reducing twice-around leakage.

To summarize, the straight-through leakage of Beam A can be nulled by deliberately adding p-polarization; the leakage of Beam B into the target path can be controlled by adjusting the Local polarizer and the Target QWP, and the twice-around leakage can be minimized with attenuation in the target path.

To optimize the polarizations of a heterodyne interferometer it is vital to have real-time feedback on the magnitude of the leakage components contributing to the cyclic error. A spectrum analyzer was used to monitor the heterodyne frequency (ν_A - ν_B) at the output of the Signal photodetector. If the Target retro is slewed at a constant velocity w, the spectral line splits into 3 components: (a) the desired signal at the Doppler-shifted heterodyne frequency (ν_A - ν_B - 2 w/λ); (b) the unshifted heterodyne frequency (ν_A - ν_B), arising from all the leakage terms except the twice-around A_{2Ts} (blocking the target path isolates the effect of A_{Ls} and A_{Lp}); and (c) the double-Doppler shifted heterodyne frequency (ν_A - ν_B - 4 w/λ) from the twice-around leakage. Driving the Target retro with a low frequency (f < 1 Hz) reciprocating triangular waveform is a practical alternative to a constant velocity. This technique provides real-time feedback with very high dynamic range, and can be used in the presence of air turbulence and vibration.

The following procedure was used to optimize the performance of a heterodyne interferometer with the configuration shown in Fig. 1. It is important to first minimize other possible sources of leakage, as discussed below. The target retro modulation is turned off for steps 1–3.

1. Coalign Beams A and B. One approach is to block the target path, deliberately introduce A_{Tp} leakage by rotating the Target Polarizer a little, and then adjust alignments to maximize this leakage signal on the spectrum analyzer.
2. Unblock the target path and adjust all polarizers, QWPs and retro-reflectors to maximize the signal.
3. Block the target path between the Main PBS and Target retro. Iteratively adjust the Target and Signal polarizers to minimize the leakage power.
4. Unblock the target path. Turn on the Target retro modulation. Iteratively adjust the Local polarizer and two QWPs to minimize components (b) and (c) of the spectrum.

Prior to step 3, the leakage power at the output of the photodetector was approximately 30 dB below the signal, corresponding to the 3 nm cyclic error expected from straight-through leakage.

Step 3 reduced the straight-through leakage from –30 dB to –80 dB, i.e. a 3 nm contribution to cyclic error is reduced to approximately 10 pm. After step 4, all leakage components of the spectrum were less than 50 dB below the signal – equivalent to a cyclic error amplitude of 300 pm.

The isolation achieved with the polarization tuning technique depends only on the polarizing properties of the optical system. It is insensitive to changes in the intensity of Beams A and B, and to the response of the photodetectors. This leads to good stability which was verified experimentally.

Other sources of leakage should be minimized prior to implementing the technique described here. In particular, reflections from the exposed ends of optical fiber in the four collimators generate a myriad of possible leakage paths. Angle-polished fibers should be used throughout to mitigate against this. Electrical cross-talk should also be addressed, with independent power supplies for the photodetectors and good isolation between the signal paths to the phase meter.

In conclusion, we have demonstrated a passive technique to reduce the amount of cyclic error in heterodyne displacement interferometers using only adjustments of existing polarizers and quarter-wave plates. Straight-through leakage of the target beam is reduced by 5 orders of magnitude. The overall cyclic error for a laboratory system operating at a wavelength of 1320 nm was reduced by a factor of 10, from 3 nm to 300 pm. The technique requires no additional detectors or signal processing, and can be used either alone, or to further improve the performance of other approaches to error-reduction.

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Table 1: Components of light incident on Signal Polarizer

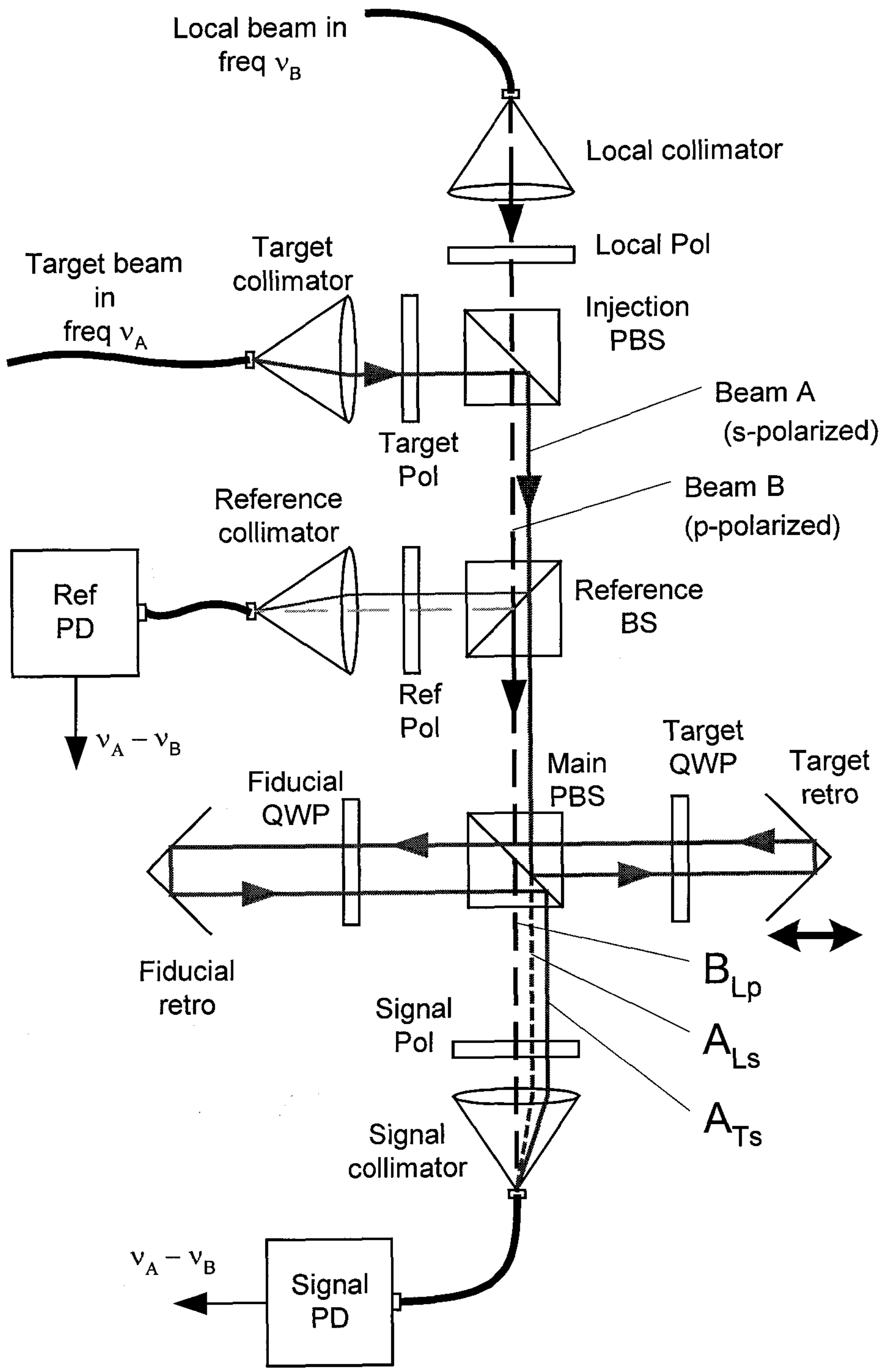
#	Label	Description	Rel. power
1	A_{Ts}	Desired target beam	1
2	B_{Lp}	Desired local beam	1
3	A_{Ls}	Straight-through leakage in Main PBS	0.001
4	A_{Lp}	p-pol component of Beam A	adj
5	A_{Tp}	Non-ideal QWPs and PBS leakage	adj
6	B_{Ls}	s-pol of Beam B & Main PBS leakage	adj
7	B_{Ts}	s-pol component of Beam B	adj
		Main PBS leakage and non-ideal QWPs	adj
8	B_{Tp}	Main PBS leakage and non-ideal QWPs	$\sim 2\times10^{-6}$
9	A_{2Ts}	'Twice-around' Main PBS leakage	0.001

Notation: A & B refer to beams A and B with frequencies ν_A and ν_B; T & L refer to Target and Local propagation paths; s & p refer to the linear polarization state with respect to the Main PBS. "adj" = adjustable – see main text. Relative power column assumes no optical loss in the target path.

Figure Captions

Figure 1: Schematic heterodyne interferometer for measuring displacement of target retro-reflector with respect to fiducial retro-reflector. Pol = Polarizer; PBS = Polarizing Beamsplitter; BS = Non-polarizing Beamsplitter; QWP = Quarter-Wave Plate; PD = photodetector. Labels B_{Lp}, A_{Ls} and A_{Ts} are described in main text. Fibers are single-mode polarization maintaining. Beams are coaxial; spatial offsets are shown for clarity only.

Figure 2: Schematic electric field vectors for 4 components of the light incident on the Signal Polarizer. S- and P-polarization states are defined with respect to Main PBS. If the leakage term L_{1p} has equal amplitude to L_{1s}, the resultant dotted vector is nulled by the Signal Polarizer.



Local beam in
freq ν_B
Local collimator
Local Pol
Target beam
in
freq ν_A
Target
collimator
Injection
PBS
Beam A
(s-polarized)
Target
Pol
Beam B
(p-polarized)
Reference
collimator
Ref
PD
Reference
BS
Ref
Pol
$\nu_A - \nu_B$
Target
QWP
Target
retro
Main
PBS
Fiducial
QWP
Fiducial
retro
B_{Lp}
Signal
Pol
A_{Ls}
A_{Ts}
Signal
collimator
$\nu_A - \nu_B$
Signal
PD

Figure 1

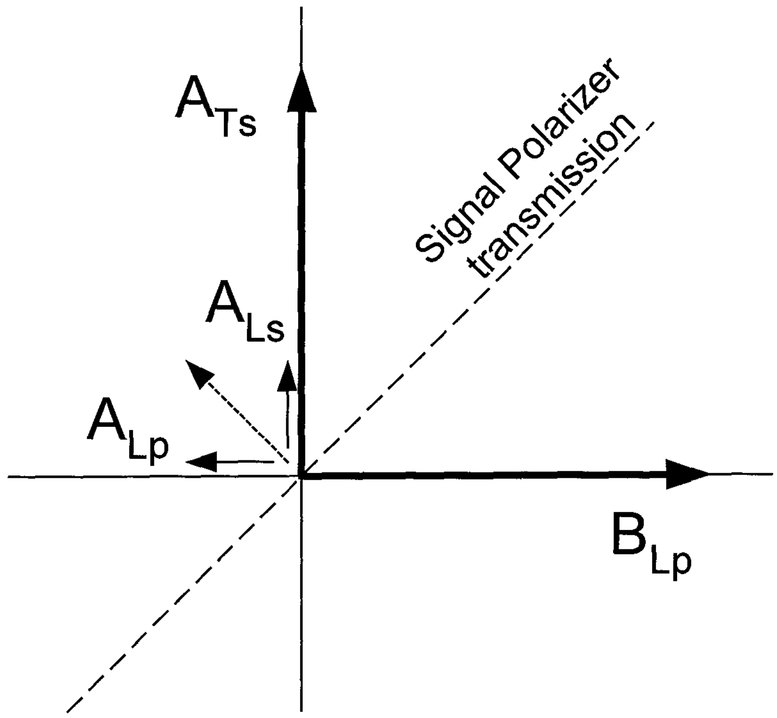


Figure 2